A 'Meandrop' Method for the Characterisation of a Sprinkler Spray in a Two-Phase CFD-Particle Tracking Model - An Improved Alternative to the 'Superdrop' Method

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ABSTRACT

The 'superdrop' method, which characterises a sprinkler as a statistical representation of a number of real drops, has been revisited. The intensive experimental data of a Wormald 'A' cu/p sprinkler in the pendant position has been used for its development, optimisation and evaluation. An alternative 'meandrop' method, which characterises the sprinkler spray by a simplified representation of the drop-diameter histogram associated with each emission sector of the spray, has been proposed to rectify the limitations associated with the need to use statistical distributions and weighting adjustment methods in the superdrop method. The superdrop and meandrop methods for characterising the sprinkler have been implemented in the two-phase multi-cell zone sprinkler model SPLASH and the two-phase CFD JASMINE-SPARTA sprinkler model. The sensitivity of the predicted heat transfer on the spray to the number of superdrops or meandrops released per emission sector, and the effect of the sprinkler on the buoyant hot smoke layer due to a fire in an enclosure have been examined.

KEY WORDS: CFD model JASMINE, Sprinkler Particle Tracking Algorithm SPARTA, two-phase multi-cell zone model SPLASH, 'superdrop' method, 'meandrop' method, Wormald 'A' cu/p sprinkler

INTRODUCTION

Traditionally sprinklers are used to protect property, but there is growing awareness of their potential for enhancing life safety. Sprinklers are used to control and limit the development of a fire within a building. Recent studies have shown that sprinklers can cool smoke layers, and can under some circumstances cause down-drag of smoke. Conversely, the presence of a smoke extraction system may delay the operation of sprinklers. The atomisation of a typical sprinkler spray produces of the order of 10^8 water drops in the air at any instant of time. Current computing resources do not allow any computer program to store the position, velocity, temperature and diameter of each of these drops, recalculating them at each time step as they move. The development of a simplified method for the characterisation of a sprinkler spray is, therefore, an essential part of a two-phase CFD particle-tracking model. The simplified method allows real sprinkler characteristics to be incorporated in the model. The superdrop method [1] for the characterisation of a sprinkler spray was presented at the Fifth Fire Safety Science Symposium.

In the present study, the superdrop method has been incorporated into the two-phase SPLASH model [2-5] and the JASMINE-SPARTA model [1,6,7]. Both SPLASH and JASMINE-SPARTA models use particle-tracking formulation for the treatment of the sprinkler drops but differ in the treatment of the gas phase. SPLASH uses simplified zonal treatment for the flowing hot gas layers whereas the JASMINE-SPARTA model uses the computational fluid dynamics approach for the gas phase, which also requires a simplified representation (e.g. 'superdrop' concept) for the sprinkler.

The present paper presents the optimisation and evaluation of the superdrop method, and then describes an alternative meandrop method for sprinkler characterisation, allowing real characteristics of a sprinkler to be incorporated in a CFD-particle tracking formulation. The following section provides a brief description of the SPLASH sprinkler particle-tracking model and the two-phase JASMINE-SPARTA model. SPLASH will be used to optimise the superdrop method and evaluate its performance against the meandrop method. The JASMINE-SPARTA model will then be used to examine the interaction of the sprinkler spray with thermally buoyant hot gas layer, and its influence on the hot combustion products due to a fire in an enclosure.

MODELLING OF GAS-DROP INTERACTION

SPLASH Model

The three-dimensional Lagrangian particle tracking model SPLASH, has been developed over a number of years at South Bank University [2-5] to describe and examine the interactions between sprinkler sprays and thermally-buoyant layers of fire gases. The building scenario for SPLASH is a corridor-like geometry e.g. a shopping mall of specifiable dimensions. The stratified smoke layer flows along the space where it interacts with a sprinkler or sprinkler array. After passing through the sprinkler(s) the gases flow through a choice of exit conditions. The model uses a simplified treatment of the gas phase that is divided into control volumes with empirical "buoyancy" profiles providing temperature and velocity profiles for a uni-directional gas layer flowing in a corridor type enclosure (with no vertical or lateral interactions). It uses a detailed and intensive representation of the sprinkler drops, incorporating measured drop-data samples from a given sprinkler at a particular location.

The experimental data were collected using the Photographic High-speed Imaging Laser technique [3,8] comprising a synchronised, pulsed copper-vapour laser light source, and a high-speed cine system along with digital image analysis equipment. Each data set contains the droplet diameter, emission factor (i.e. the relative frequency of a particular drop) and the horizontal and vertical velocity components, for a large number of drops. Several such data sets sampled at certain angles (both vertically and horizontally) around the sprinkler are used directly in SPLASH to provide the initial drop distributions around the sprinkler head, which can then be tracked by the Lagrangian particle-tracking technique to produce the drop trajectories, size and temperature histories. The direct use of the intensive experimental data (1670 drops per sample for the Wormald 'A' cu/p sprinkler in the pendant position) provides an accurate characterisation of the sprinkler drops in the model.

JASMINE-SPARTA Model

The detailed mathematical description of JASMINE-SPARTA sprinkler model can be found elsewhere [1]. Suffice it to say here that it uses a Eulerian-Lagrangian approach [9] for modelling sprinkler/fire-gas interactions by tracking discrete sprinkler drops (Lagrangian phase) as they move through the fire gases (Eulerian gas phase). SPARTA (Sprinkler Particle Tracking algorithm) [7] is based on the Particle-Source-In-Cell (PSI-Cell) method developed by Crowe et al. [10]. An initial gas flow field, existing prior to sprinkler operation, is calculated for the particular scenario being represented. The drop trajectories, size and temperature histories are then obtained by numerically integrating the equations of motion for the drops moving through this initial gas flow field. The drops act as sources of mass, momentum and enthalpy to the gaseous phase. The gas flow field is then recalculated with these sources present and the drops are again tracked through the updated gas field. This procedure is repeated (track drops, calculate sources, update gas field) until a converged solution is obtained.

MODELLING OF SPRINKLER

The superdrop and meandrop methods for characterising a sprinkler spray have been examined here. The differences between them are as follows:

The superdrop method [1] uses a log-normal distribution (with mean and standard deviation derived from experimental data) to generate a set of initial droplet diameters. The weighting (i.e. number of real drops a given drop actually represents) of all the droplets generated in a given sector is the same (the method relies on the fact that in accordance with the log-normal distribution more smaller drops than large will be generated to obtain an overall droplet population). The method uses the same normal distribution (i.e. the same mean and standard deviation) to generate all of the horizontal/vertical droplet velocity components (independent of diameter) for each drop. One half of the sprinkler circumference was split into a total of 9 azimuthal emission sectors, with data sets for each sector being generated using one of the fitted distributions A, B, C, D or E.

The meandrop method derives a frequency histogram from the experimental droplet diameter data and uses the midpoint of each diameter interval, or bin, as a representative drop diameter size, referred to as the 'meandrop' diameter. From the histogram each drop size has corresponding weighting (relative frequency), referred to as the 'meandrop' weighting, which determines the number of actual drops it represents. The method uses a different normal distribution (i.e. different mean and standard deviation) to generate each of the horizontal/vertical droplet velocity components for every diameter droplet size being represented. The standard deviation of the velocity components gives a spread of velocities for each diameter interval.

The characterisation of droplet diameters used in the meandrop method is similar in approach to that used previously by Crowe et al. [10] and researchers at Factory Mutual in the 1980's and 1990's [e.g. Ref. 11] (although they use drop volume distributions rather than drop number frequency distributions used here). However, both the meandrop and the superdrop characterisation methods described here also include the droplet velocity distributions and derive from an intensive set of experimental data.

Examination of the 'Superdrop' Method

The introduction of the superdrop method [1] raises the following questions:
How well does the superdrop distribution characterise the spray?
How many 'superdrops' should be released at each time step and in total?

To help answer these questions, the superdrop and intensive data sets were used with SPLASH for investigating the effect of sprinkler drop characterisation on heat transfer from the hot gas to the spray. As an illustrative test case, a 1.5 m deep smoke layer was considered in a 3 m high compartment having a plan area of 10 m x 10 m. The hot layer was characterised by a vertical profile of gas temperature ranging between 446K close to the ceiling and 346Kat the base of the layer and gas velocity ranging between 3.4 m/s close to the ceiling and 0.8 m/s at the base of the layer. Figure 1 illustrates the sensitivity of increasing the number of superdrops released per time step by each emission sector on the predicted heat transfer from the fire gases to the drops. The dotted line shows the predicted heat transfer value of 130 kW using the intensive data. The solid line shows the superdrop predictions. It should be noted that for each superdrop data set, the superdrop weighting has to be adjusted to give the pre-specified sprinkler flow rate. Thus, when only one new superdrop is released by every sector, and the weighting is adjusted over a set of just 18 superdrops, there is a large over-prediction of the heat transfer in comparison with the intensive data figure. Increasing the number of new superdrops released by each emission sector reduces this discrepancy as the heat transfer value approaches that predicted using the intensive data. These results suggest that for realistic heat transfer predictions of the superdrop method, at least 5 to 10 superdrops should be released by each emission sector at each time interval. It is worth pointing out that the superdrop distribution is biased towards the smaller diameter drops, producing larger number of smaller drops with higher total surface area and thus more heat transfer to the spray than the original intensive data set.

Examination of the 'Meandrop' Method

Figure 2 shows the results of applying the 'meandrop' method, to the intensive sprinkler data sampled for the Wormald 'A' (cu/p), K-80 sprinkler head. By using five diameter bins for each of the emission sectors (A-E), the meandrop method gives a total of 25 drops to characterise the quadrant. Note that for the superdrop method sector E subtends the angle 70°-110°, whereas for the meandrop method sector E subtends the angle 70°-90°, providing more flexibility for rotations of the sprinkler head data. Each sector can be represented by a drop-diameter histogram with five meandrops, each meandrop being characterised by a diameter, a weighting, and the horizontal and vertical velocity component means and standard deviations.

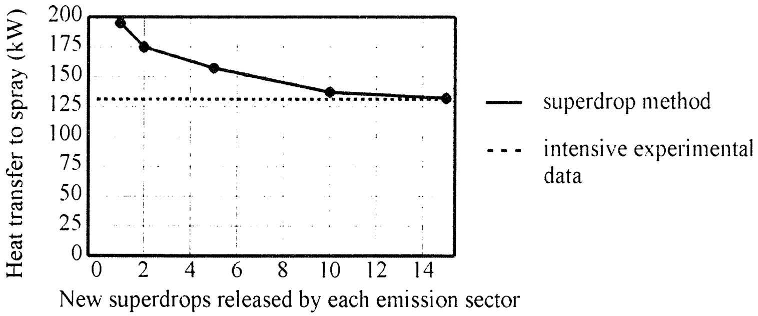


Figure 1. The effect of increasing the number of superdrops released per sector on the heat transfer to the spray using SPLASH, for the superdrop method.

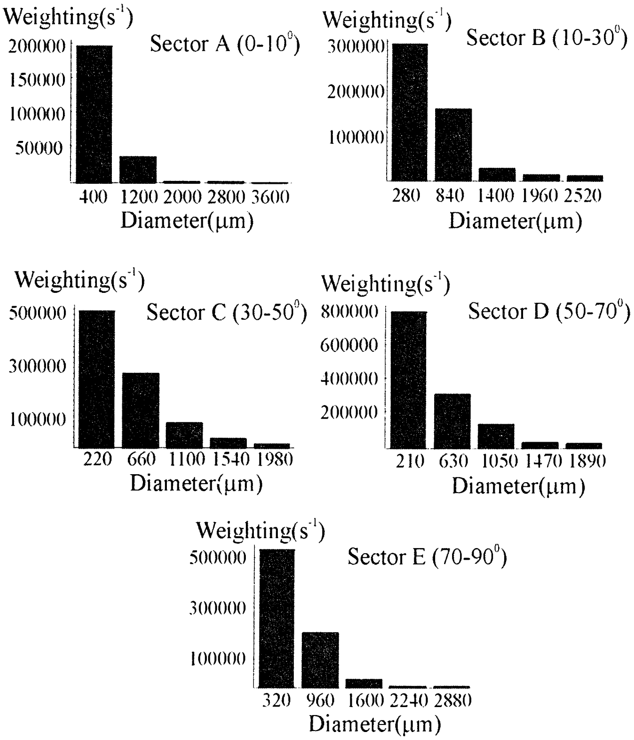


Figure 2. Meandrop diameter/weighting histograms for the five intensive data emission sectors, using five meandrops.

Figures 3 and 4 show the corresponding intensive drop data for the horizontal and vertical velocity components against drop diameter, together with the mean velocity values and standard deviations calculated for each meandrop. Figure 5 shows the heat transfer results predicted by SPLASH using meandrop data sets with different number of meandrops, for the same configuration as used to test the superdrop method in the previous section. It can be seen from the figure 5 that using a reduced drop data set with just three diameter-intervals per emission sector produces a heat transfer result within 10 % of the intensive data value. Increasing the number of bins further gives an improved heat transfer value, close to that of the intensive data.

The SPLASH predictions with meandrops suggest that even with relatively coarse diameter intervals the meandrop method is a reasonable approximation to the intensive data. This is due to the fact that it makes fuller use of experimental data than the superdrop method, whilst still reducing it into a more compact form suitable for use with the JASMINE-SPARTA sprinkler model.

The advantages of the meandrop method over the superdrop method are as follows:

- Since the meandrop diameters are fixed and the corresponding weightings are determined directly from the intensive data, the weightings for each drop release set are automatically normalised to give the correct flow rate upon release (to a good approximation).
- The method can be made completely deterministic. This can be advantageous when trying to obtain a converged steady-state solution.
- The meandrop method gives direct representation of the measured diameter distribution, whose refinement can be adjusted by reducing the interval size.
- The method can reflect any patterns and irregularities present in the intensive experimental data (e.g. diameter intervals with no drops present).
- It avoids making assumptions about drop-diameter distribution (e.g. Log-normal).
- The method is applicable to any experimental sprinkler data.

The disadvantages of the meandrop method are as follows:

- The performance of the meandrop method depends on the quality of the intensive experimental data set used.
- The meandrop method may not accurately incorporate the effect of smaller drops if drop-diameter intervals are too coarse.

JASMINE-SPARTA SPRINKLER MODEL

Numerical Simulations

A series of numerical simulations using the JASMINE-SPARTA model were performed for studying the sensitivity on the heat transfer to the sprinkler spray of increasing the number of superdrops and meandrops and size distributions.

The plan and side view of the three-dimensional enclosure used [12] for the simulations is shown in Figure 6. The enclosure is 15 m long, 6 m high and 7.5 m wide. It is fully open at the right-hand end. The fire source with a heat release rate of 1 MW was situated symmetrically

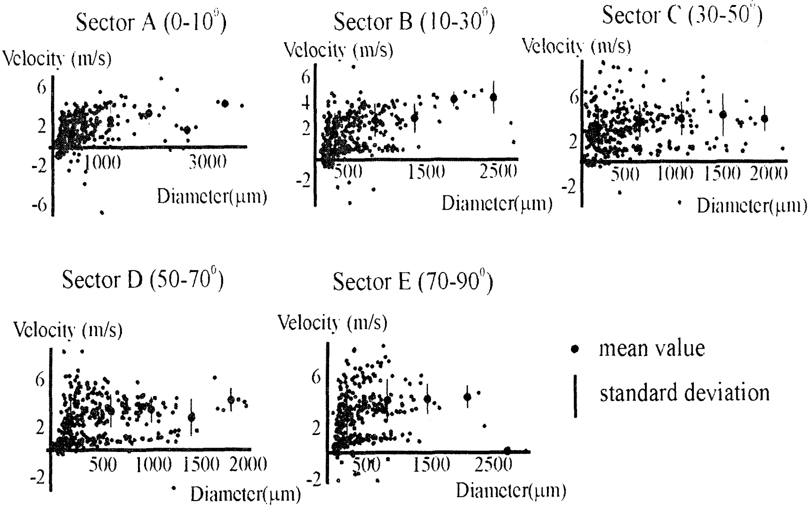


Figure 3. Fitted normal distributions for horizontal velocities versus diameter for the intensive drop data using 5 meandrops per sector.

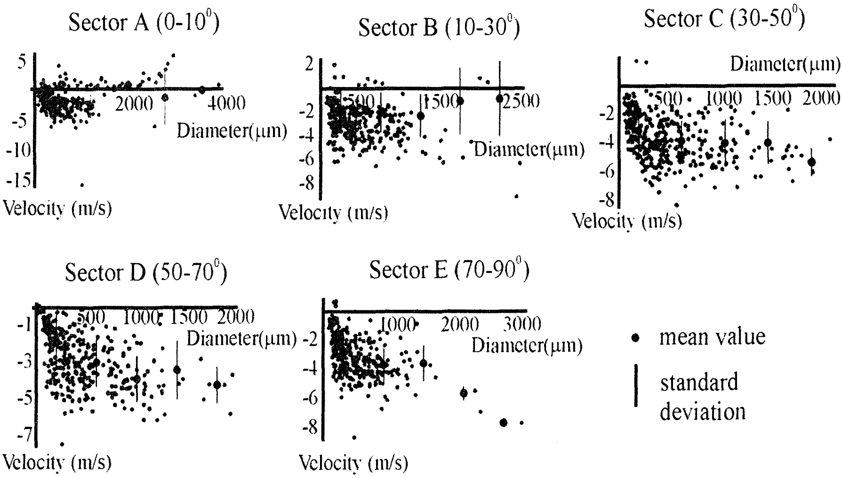


Figure 4. Fitted normal distributions for vertical velocities versus diameter for the intensive drop data using 5 meandrops per sector.

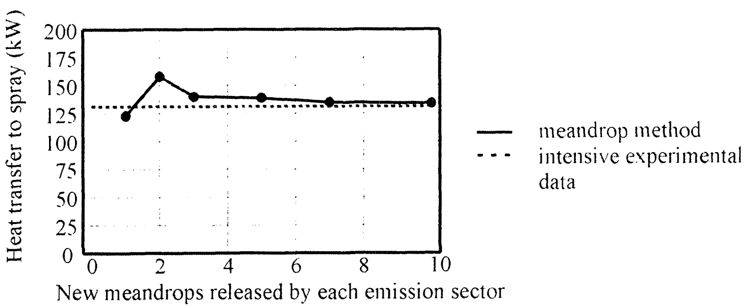
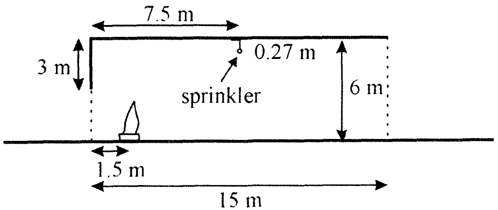
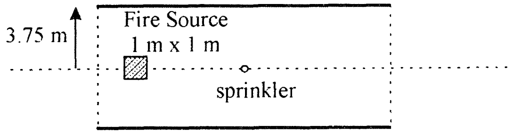


Figure 5. The effect of increasing the number of meandrops released per sector on the heat transfer to the spray, using SPLASH, for the meandrop method.



(a) side view



(b) plan view

Figure 6. Schematic of the enclosure geometry.

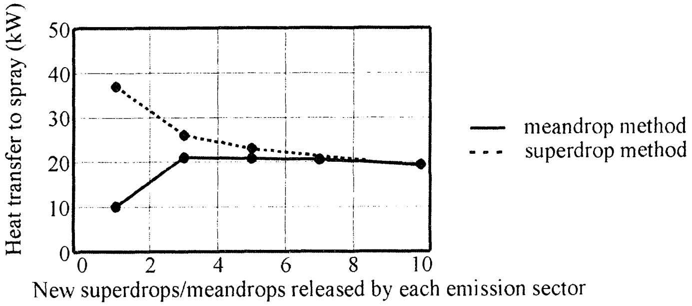


Figure 7. The effect of increasing the number of superdrops or meandrops released per sector on the heat transfer to the spray, using JASMINE-SPARTA model.

on the floor centre-line, 1.5 m from the left end of the enclosure. A Wormald 'A' CU/P, K-80 sprinkler was located centrally inside the enclosure 270 mm below the ceiling. Because of symmetry, half the enclosure was modelled. The computational domain was extended by about 4m on each end along the enclosure.

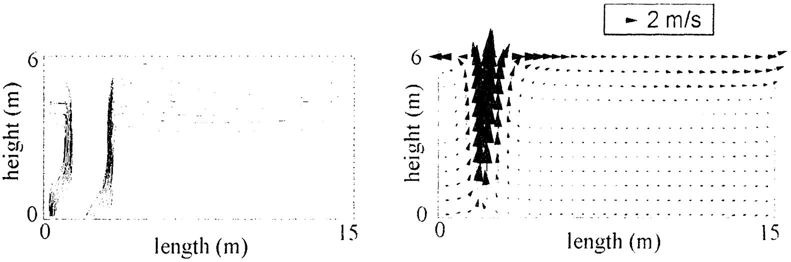
The converged steady-state solution for flow field, prior to the sprinkler operation, was used as the starting point for simulating the conditions after sprinkler operation. A sprinkler with a flow rate of 60 l/min was subsequently introduced. The superdrops or meandrops were released from the sprinkler head every 0.1s, but were tracked more frequently at an interval of 0.01 s.

Results and Discussion

Figure 7 shows the dependence of the heat transfer from the gas to the spray, predicted by the JASMINE-SPARTA sprinkler model, on the number of superdrops or meandrops released at each time interval, for the corresponding superdrop or meandrop method. It is apparent from the figure that a measure of convergence in the predicted heat transfer can be achieved by increasing the superdrop number released per time step to 5 or above. This behaviour follows the pattern found using the superdrop method in SPLASH, where the heat transferred from the hot gas to the spray was over-estimated when the number of drops the weighting adjustment is small. This occurs as a result of the superdrop distribution being biased towards the smaller diameter drop sizes (producing distributions with higher total surface area) and consequently more heat being transferred to the spray. The present JASMINE-SPARTA predictions of the heat transfer to the spray are consistent with the earlier SPLASH predictions shown in figure 1, suggesting that at least 5-10 superdrops per emission sector would be necessary to reproduce the heat transfer value obtained by using the intensive data. It can also be seen that the heat transfer predicted by the superdrop method is too high with low numbers of superdrops, while the heat transfer predicted by the meandrop method is relatively consistent for nearly all drop numbers.

Figure 8, shows the smoke temperature contours and flow field for the vertical plane along the centre-line of the enclosure, predicted by JASMINE prior to sprinkler operation. These reveal the expected pattern of behaviour with a strong thermal plume present above the fire and hot smoke flowing out of the upper part of the open corridor to the right. This hot upper gas flow is approximately 2 m deep and stratified into thermal layers, with temperature increasing with height from 20°C to 55°C. In particular, a prominent contour of hot smoke approximately 1 m deep, with temperatures ranging from 50-55°C is present just beneath the ceiling, extending the length of the corridor to the right of the fire plume. The other contour lines form thin temperature bands roughly parallel to the ceiling. Cold air is entrained into the lower half of the plume beneath the soffit to the left and through the lower portion of the vent to the right.

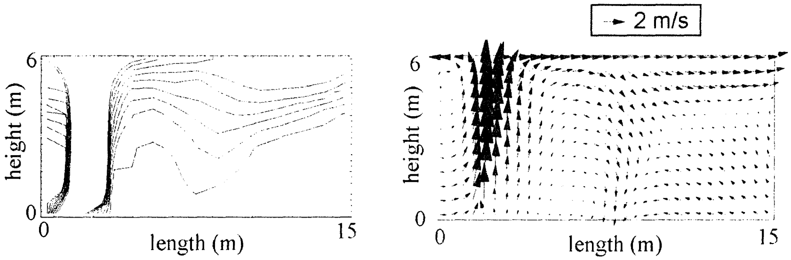
Figure 9, shows the effect of the sprinkler on the gas temperatures and flow field predicted by JASMINE-SPARTA model, using the superdrop method, when 45 new superdrops are released at each time interval. The temperature contours reveal that the original upper smoke layer to the right of the fire plume has been cooled down, with the upper temperature contour now lying in the 45-50°C range. The lower temperature contour regions are considerably thicker and have been effectively pulled downwards by the spray to lower heights, producing a bulge. For example the 25-30°C contour region, which originally occupied a thin band at a height of about 4.0 m,



(a) Gas temperature contours
(beginning at 20°C and at 5°C intervals)

(b) Velocity vectors

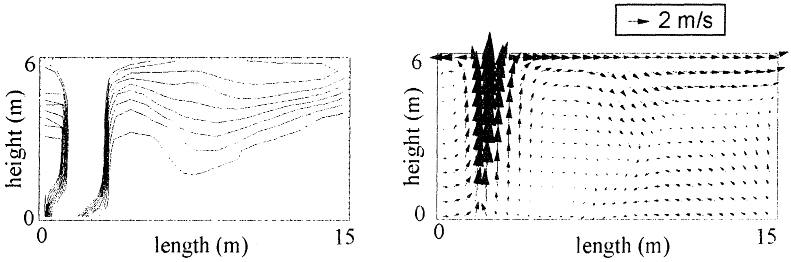
Figure 8. Steady state JASMINE predictions on the vertical central plane prior to sprinkler activation.



(a) Gas temperature contours
(beginning at 20°C and at 5°C intervals)

(b) Velocity vectors

Figure 9. Steady state JASMINE-SPARTA predictions on the vertical central plane after sprinkler activation with 45 superdrops released at a time.



(a) Gas temperature contours
(beginning at 20°C and at 5°C intervals)

(b) Velocity vectors

Figure 10. Steady state JASMINE-SPARTA predictions on the vertical central plane after sprinkler activation with 50 meandrops released at a time.

is thicker and bulges downwards to a height of around 3 m. The flow field directly to the right of the plume shows that the superdrops have induced a considerable distortion. This results in a region of strong downward gas flow from just below the ceiling from the sprinkler down to the floor and recirculation back into the plume, shifting the upward flow further to the right.

Figure 10 shows the effect of the sprinkler on the gas temperatures and flow field predicted by the JASMINE-SPARTA sprinkler model, using the meandrop method (using mean velocities), when 50 new meandrops are released at a time (i.e. using 5 diameter intervals to characterise each emission sector as shown in figure 5). The gas temperature contours follow a qualitatively similar pattern to the superdrop results, with a downward distortion and expansion in width of the lower temperature contours induced by the sprinkler flow. However the downward bulge is less pronounced. The magnitude of the temperature change in the upper gas flow is also lower, with the flow region directly below the ceiling remaining in the 50-55°C range. The predicted results are again qualitatively similar to the pattern found using the superdrop method, showing a downward gas flow induced by the spray. However, it can be seen from the flow field predictions that the magnitude of the downward gas flow is lower, and does not penetrate so far down before recirculating into the flow entrained back into the plume.

CONCLUSIONS

The relative merits of the meandrop method over the superdrop method for the characterisation of the sprinkler spray have been highlighted by comparison with the original intensive data and by using the superdrop and meandrop data sets with SPLASH. The original superdrop distribution (based on one superdrop per emission sector) produces an inadequate match to the original intensive data, which is reflected in large discrepancies between the intensive and superdrop results produced when using the distributions in SPLASH. In order to match the flow rate of the sprinkler with the superdrop distribution the superdrop weightings must be modified. The superdrop data distributions and the predicted heat transfer are highly sensitive to the method used for the adjustment of drop weightings.

The SPLASH predictions indicate that for the superdrop method, at least 5 to 10 'superdrops' should be released at each time-step interval. In contrast to the superdrop method, the meandrop method offers a direct reduction of the intensive data (meandrop diameter defined as mid-point of the drop-diameter interval) and hence does not require a weighting adjustment method for matching the pre-specified flow rate. Since the weighting adjustment was a major source of error for the superdrop method, this is a significant advantage. The method also allows a direct representation of the experimental distribution, reflecting any patterns and irregularities present and can be made completely deterministic. Its implementation in SPLASH suggests that the meandrop data with 5 diameter intervals for each emission sector provide a reasonably good characterisation of the intensive spray data.

The trends in behaviour of both the superdrop and meandrop method predicted by SPLASH appear to be confirmed by the JASMINE-SPARTA sprinkler model simulations as the number of new superdrops or meandrops released each time interval is increased. From these results, it is recommended that a minimum of between 5 and 10 new superdrops or 5 meandrops per emission sector should be released at each time interval to achieve an acceptable consistency for heat transfer predictions. The temperature contours and flow fields show the effect of the sprinkler drops on the gas field, producing a cooler upper compartment region and hotter lower compartment region as the gas flow is dragged downwards by the sprinkler spray.

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